IMPACT OF HADRONIC DECAYS OF THE LIGHTEST NEUTRALINO ON THE REACH OF THE CERN LHC

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Abstract

If R-parity is not conserved, the lightest supersymmetric particle (LSP) could decay via lepton number violating or baryon number violating interactions. The latter case is particularly insidious since it leads to a reduction of the $\not{E}_T$ as well as leptonic signals for supersymmetry. We evaluate cross sections for jets plus $\not{E}_T$, 1ℓ, 2ℓ (same-sign and opposite sign) and 3ℓ event topologies that result from the simultaneous production of all sparticles at the CERN Large Hadron Collider (LHC), assuming that the lightest supersymmetric particle $\widetilde{Z}_1$ decays hadronically inside the detector via R-parity violating interactions. We assume that these interactions do not affect the production rates or decays of other sparticles. We examine the SUSY reach of the LHC for this "pessimistic" scenario, and show that experiments at the LHC will still be able to search for gluinos and squarks as heavy as 1 TeV, given just 10 fb^{-1} of integrated luminosity, even with cuts designed to explore the canonical SUSY framework with a *conserved* R-parity.

It is generally accepted that a decisive search for weak scale supersymmetry (SUSY) will require the direct exploration of the TeV scale. This would be possible, for instance, at the CERN Large Hadron Collider (LHC) where experiments should be able to probe gluino and squark masses up to about 2 TeV [1–3]. The large reach of the LHC provides a comfortable safety margin beyond the, admittedly subjective, upper limits of $\sim 800-1000$ GeV on sparticle masses [4] from the requirement that SUSY stabilize the scalar electroweak symmetry breaking sector. These analyses of the reach of the LHC are, however, performed within the framework of the minimal supersymmetric model where it is assumed that the three gaugino masses and the various sfermion masses unify at some ultra-high energy scale $M_X \sim M_{GUT}$. Moreover, it is also assumed that R-parity is conserved so that the lightest supersymmetric particle (taken to be the lightest neutralino, $\widetilde{Z}_1$) escapes detection, leading to the canonical $\not{E}_T$ signature for SUSY. In view of the importance of the issue, it is worthwhile to ask how the LHC reach would be altered if these assumptions are relaxed: in particular, could it happen that signals from kinematically accessible sparticles can remain hidden at the LHC?

The gaugino and sfermion mass unification conditions mainly imply that coloured sparticles are heavier than their colourless counterparts; i.e. gluinos are heavier than charginos and neutralinos, and squarks are not lighter than sleptons. If the situation were reversed and the coloured sparticles are light, they would be even more copiously produced at the LHC, and so, would be detectable via the $\not{E}_T$ signature as long as we assume that the lightest SUSY particle (LSP) is electrically and colour neutral and escapes experimental detection. SUSY phenomenology would be quite different since the cascade decays of gluinos and squarks which lead to the multilepton signatures would be suppressed, and further, the production of colourless particles (*e.g.* chargino and neutralino production) would dominantly lead to hadronic final states if the gluino were lighter than $\widetilde{W}_1$ or $\widetilde{Z}_2$. It is, however, hard to imagine that (barring any artificial degeneracies that drastically reduce the visible energy in all SUSY events) gluino and squark signals would escape detection [5], at least in the $\not{E}_T$ channel.

In our study of whether SUSY can possibly remain hidden at the LHC, we are thus led to consider scenarios where the LSP decays inside the detector via explicit [6] R-parity violating interactions [7], so that $\not{E}_T$, the usual hallmark of SUSY events, is greatly degraded. The phenomenology of R-parity violating models can be very different from that of the minimal model. R-violating interactions, if they are sufficiently strong, can alter the decay patterns of all sparticles. These interactions also lead to new sparticle production mechanisms: in particular, squarks and sleptons can be singly produced as resonances at colliders. The resulting modifications are, in general, sensitively dependent on the strength and flavour structure of the R-violating interactions, but are negligible if the corresponding couplings are much smaller than gauge couplings. We will assume this to be the case in our analysis. Then, the only impact of these R-parity violating interactions on collider phenomenology is that they cause the LSP to decay inside the detector, thereby greatly reducing the $\not{E}_T$ signal.

With the field content of the minimal model, R-parity violation can occur via renormalizable operators that also violate either lepton or baryon number conservation. While some of these couplings are indeed significantly constrained by experiment [8] (non-observation of proton decay strongly constrains the simultaneous presence of baryon and lepton number violating operators), it is possible to build perfectly viable R-violating models, especially if we

assume that these R-violating couplings are much smaller than gauge couplings (but large enough so that the LSP decays within the detector). The decay patterns of the LSP depend on the structure of R-violating interactions. If R-parity conservation is broken by lepton number violating operators, the LSP decays either via $\widetilde{Z}_1 \to \ell_i \bar{\ell}_j \nu$ or via $\widetilde{Z}_1 \to \ell q_i \bar{q}_j, \nu q_i \bar{q}_j$ (i, j denote family indices) with parameter-dependent branching fractions. The main point to note is that the decays of each LSP lead to additional isolated leptons in the final state. In the favourable case where the LSP only decays into electrons and muons (say via $\widetilde{Z}_1 \to \bar{e}\mu\nu_e$, for example), every SUSY event contains at least four leptons from the decays of the two LSPs, and can readily be separated from Standard Model backgrounds. In this case, experiments at even the Tevatron Main Injector (MI) upgrade at Fermilab should be (indirectly) sensitive to gluinos as heavy as 700-800 GeV [9], and the reach of the LHC should be truly enormous. If, on the other hand, R-parity is violated by baryon number violating operators, the LSP can only decay purely hadronically via $\widetilde{Z}_1 \to q_i q_j q_k$ and its charge conjugate mode. The hadronic decays of the LSP impact upon the SUSY signal in two distinct ways. First, the usual $\not{E}_T$ signal is greatly reduced as we have already mentioned. Second, the additional hadronic activity from the decays of the LSP make it more difficult for the leptons from the cascade decays of gluinos and squarks to remain isolated so that the SUSY reach via leptonic channels is also reduced. Gluinos heavier than about 200 GeV could evade detection at the MI [9] if this scenario is operative.

The purpose of this paper is to examine the reach of the LHC within the same scenario, with a view to see whether sparticle signals could possibly be missed in LHC experiments [10]. It seems reasonable to suppose that the first searches for SUSY at the LHC will be performed with the minimal (R-parity conserving) framework in mind; *i.e.* using cuts roughly along the lines of the analyses in Ref. [1–3] which gave similar results for the SUSY mass reach within the minimal model framework. Here, we therefore examine the SUSY reach of the LHC in the $\not{E}_T$, 1ℓ, opposite-sign (OS) dilepton, same-sign (SS) dilepton and 3ℓ channels, using the same cuts (we do not list these for brevity) as in our earlier analyses [3] of the R-parity conserving case. We stress that these cuts are not optimized for searching for SUSY when R-parity is violated. Our purpose here is to roughly delineate the region of parameter space where the initial searches for supersymmetry will lead to an observable signal.

For definiteness (and to be able to compare with our previous analyses within the R-parity conserving framework), we use the minimal SUGRA model as discussed in Ref. [3], and assume that the superpotential term $\lambda''_{cds} C^c D^c S^c$ is the only source of R-parity violation [9]. We note that as long as the coupling λ''_{cds} is much smaller than the gauge couplings, it makes a negligible effect on the masses and couplings obtained using renormalization group evolution, so that the production mechanisms and decay patterns of all sparticles (other than the LSP) are unaltered from minimal model expectations. The LSP, however, decays via $\widetilde{Z}_1 \to cds$ or $\widetilde{Z}_1 \to \bar{c}\bar{d}\bar{s}$, with the two modes having the same branching ratio by CP invariance. Our results are insensitive to the assumed flavour structure of the R-violating interaction as long as we do not attempt any flavour tagging, and should give the maximum degradation of the signal, at least as long as these interactions do not affect the decays of heavier superparticles. The model is then completely specified by four parameters which we take to be the common scalar mass m_0, a common gaugino mass $m_{1/2}$, $\tan\beta$ and A_0 together with the sign of μ. The magnitude of the R-violating coupling only affects the LSP

3

lifetime which is irrelevant as long as it decays inside the detector [11].

Following Ref. [3], for a 100 GeV × 100 GeV grid of points in the $m_0 - m_{1/2}$ plane, we have used ISAJET 7.20 [12] to simultaneously generate all $2 \rightarrow 2$ sparticle subprocesses and the subsequent cascade decay chains as given by the model. We use CTEQ2L structure functions in our computations of the cross sections [13]. The $3q$ decays of the LSPs produced at the end of the cascade are implemented by explicit addition of decay modes to the ISAJET decay table. We use the toy calorimeter simulation package ISAPLT with the same hadronic and electromagnetic resolution smearing as in our previous analysis. Events are classified by their isolated lepton (e and μ) content into the $\not{E}_T$, 1ℓ, OS, SS and 3ℓ topologies using exactly the same cuts as before [3]. Standard Model physics background levels from $t\bar{t}$, W + jet, Z + jet production, QCD and vector boson pair production have been shown in Ref. [3] and will not be reproduced here. We consider a signal to be observable if (for any value of the floating cut parameter E_T^c defined in Ref. [3]) $i)N_S > 5\sqrt{N_B}$, $ii)$ $N_S > 0.2N_B$ and $iii)$ there are at least 5 signal events in 10 fb^{-1} of integrated luminosity at the LHC. Here, N_S is the surviving number of signal events and N_B is the surviving number of background events for our choice of integrated luminosity.

The region of the $m_0 - m_{1/2}$ plane where there is an observable signal in the various leptonic channels is shown by the various contours in Fig. 1 for $a)$ $\tan\beta = 2, \mu < 0$, $b)$ $\tan\beta = 2, \mu > 0$, $c)$ $\tan\beta = 10, \mu < 0$, and $d)\tan\beta = 10, \mu > 0$. We have taken $A_0 = 0$ and fixed $m_t = 170$ GeV. The bricked regions are excluded by theoretical constaints, and the shaded regions are excluded by experimental constraints, as discussed in Ref. [3]– the only difference is that we have updated the chargino mass limit to $m_{\widetilde{W}_1} > 65$ GeV in accord with recent LEP2 data [14]. Various sparticle mass contours are shown in Ref. [3]; here, we show only the $m_{\tilde{g}} = 1000$ GeV and $m_{\tilde{q}} = 1000$ GeV contours for clarity. Several comments are worth noting:

- The outer envelope of the maximal reach contours in all four frames extends beyond the $m_{\tilde{g}}$ and $m_{\tilde{q}} = 1000$ GeV contours. This implies that squarks and gluinos with masses smaller than 1 TeV should be observable via the canonical leptonic search channels at the LHC even in this "pessimistic" scenario. If $m_0 \leq 300 - 400$ GeV, the LHC reach extends out to $m_{1/2} \sim 800$ GeV, mainly because of the enhanced leptonic branching fractions of charginos and neutralinos [3]. This feature is common to the case where R-parity is conserved.

- Over most of the region of the $m_0 - m_{1/2}$ plane where $m_{\tilde{g}}$ and $m_{\tilde{q}} < 1000$ GeV, there are observable signals in *all* the multilepton channels. In our previous analysis, with a stable LSP, the maximal reach was attained in the 1ℓ channel. In the current case, the reach in the various leptonic channels is qualitatively similar. It is reasonable to suppose that as the charge multiplicity of the leptonic channel increases, there are typically more accompanying neutrinos, so that the signal events can pass the $\not{E}_T$ requirement more easily. Nevertheless, a comparison with Fig. 18 of Ref. [3] shows that the reach in $m_{1/2}$ via the multilepton channels is reduced by $\sim 100 - 150$ GeV relative to the R-parity conserving case.

- The regions where the leptonic signals occur extend well beyond where the $\widetilde{Z}_2$ "spoiler modes" $\widetilde{Z}_2 \rightarrow \widetilde{Z}_1 Z$, $\widetilde{Z}_2 \rightarrow \widetilde{Z}_1 H_\ell$ turn on. This indicates that a large fraction of the events come from chargino and W-boson sources which have accompanying neutrinos.

4

- In the region of parameter space where the OS dilepton signal has significant contributions from the leptonic decay of $\widetilde{Z}_2$ produced in a SUSY event cascade, we expect a large number of $e\bar{e}$ and $\mu\bar{\mu}$ pairs compared to $e\bar{\mu}$ or $\mu\bar{e}$ pairs; in contrast, for cascade decays dominantly involving leptonic decays of charginos or top quarks, we expect essentially the same number of events in each of the four dilepton flavour channels. The dilepton flavour asymmetry $A_F = \frac{N_{e\bar{e}} + N_{\mu\bar{\mu}} - N_{e\bar{\mu}} - N_{\mu\bar{e}}}{N_{e\bar{e}} + N_{\mu\bar{\mu}} + N_{e\bar{\mu}} + N_{\mu\bar{e}}}$ in OS dilepton events is thus a good indicator [15] of neutralino production in cascade decay chains. In Ref. [3] we had shown that for the case of the R-parity conserving scenario, A_F is large and observable over regions of parameter space where $\widetilde{Z}_2$ has a significant leptonic branching fraction. In contrast, for the R-violating scenario that we have been studying here, we find that A_F is small even in the small m_0 region where the leptonic decays of $\widetilde{Z}_2$ are enhanced. We attribute this to the fact that these events generally do not contain neutrinos, and so, fail to satisfy the $\not{E}_T$ requirement.

- It would be of interest to investigate whether it is possible to explicitly reconstruct the $3j$ mass bump for LSP decays, especially in the SS and 3ℓ channels which have rather small backgrounds from Standard Model sources. This may be difficult due to additional jets from the rest of the event, jet mergers, and the formidable combinatorial background from the large jet multiplicity (which would be the distinguishing characteristic of this scenario) in every SUSY event.

Before proceeding further, a technical remark about the simulation leading to the results in Fig. 1 is worth noting. For the present case, the efficiency for the signal events to pass the cuts (especially the $\not{E}_T$ cut) is considerably smaller than in the R-parity conserving case studied in Ref. [3]. As a result, especially for the small $m_{1/2}$ points, we sometimes have just about 5-10 events that pass all the cuts in our simulation, so that the signal cross sections have statistical errors as high as 30-50%. In contrast, for $m_{1/2} \geq 300$ GeV, we typically have several tens (or even hundreds) of events in our simulation, at least for $E_T^c = 100$ GeV. We have checked, however, that except for the row of points with $m_{1/2} = 100$ GeV, there are at least nine signal events in at least one of the leptonic channels, so that the detectability of the signal is assured. *This is not, however, the case for $m_{1/2} = 100$ GeV for which our simulation does not provide a definite answer because we have been unable to obtain sufficient statistics. This is not merely academic, since it leaves open the possibility that there could be a window where SUSY might escape detection at the Tevatron as well as the LHC.*

Finally, we turn to the multijet $+\not{E}_T$ signal for which we have used an isolated lepton veto. The efficiency for this signal is indeed quite small, and it is difficult to obtain a sufficiently large event sample to be able to present a contour as in Fig. 1. We have, therefore, chosen to present our results in terms of number of events in our simulation that pass our cuts for those points where the signal is observable according to our criteria. We leave it to the reader to judge the quality of the simulation and to make a personal assessment of the reach in the multijet $+\not{E}_T$ channel from this data. Points where we obtain an observable signal and for which we have at least nine events in our simulation are denoted by black squares. We consider points for which there are less than four events in our simulation as unreliable, and denote these by open squares. Gray squares denote points in between these two; here we leave it to the reader to assess the observability. Finally, the x's denote the regions of the plane where the signal falls below the observable level. The results of our simulation are

shown in Fig. 2 for the same four cases (a)-(d) as in Fig. 1. Although it may be difficult to assess the exact reach in this channel, it is clear that as anticipated, the reach is significantly smaller than in the leptonic channels. Moreover, even if we assume that there is a reach even for the points denoted by the grey squares, we see that there are significant ranges of parameters favoured by fine-tuning considerations where there will be no signal in the $\not{E}_T$ channel.

Before closing, we mention that the scenario we have devised may not be the absolute worst case scenario from point of view of detection of SUSY signals at the LHC. If baryon number violating couplings are large these could modify sparticle decay patterns: In particular, R-parity violating decays of gluinos $\tilde{g} \rightarrow q\tilde{q}^* \rightarrow qqq$, or squarks, or of even charginos and neutralinos, which do not lead to leptons in the final state could reduce the branching fractions for the usual decay chains and further reduce the leptonic cross sections. Any such analysis would be extremely model-dependent and is beyond the scope of this paper [16].

To summarize, we have shown that if gluinos and squarks are lighter than ~ 1 TeV, initial searches for sparticles at the LHC should be able to detect gluino and squark signals even if R-parity is not conserved, and the LSP decays purely hadronically via baryon number violating operators. A clear signal should be seen above Standard Model backgrounds in the 1ℓ as well as in several of the multilepton channels. The signal in the $\not{E}_T$ channel will be significantly reduced relative to expectations within an R-parity conserving framework, and may even be unobservable if such a scenario is realized in nature. In this case, a re-analysis of the LHC data with cuts optimized for R-violating decays could further improve the signal to background ratio. The main message of this analysis, however, is that it is unlikely that supersymmetry can remain hidden at the LHC if squarks and gluinos are lighter than 1 TeV, the preferred mass range if SUSY is to stabilize the electroweak symmetry breaking sector.

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REFERENCES

[1] CMS Collaboration, *Technical Proposal*, CERN/LHCC 94-38 (1994).

[2] ATLAS Collaboration, *Technical Proposal*, CERN/LHCC 94-43 (1994).

[3] H. Baer, C-H. Chen, F. Paige and X. Tata, Phys. Rev. **D52**, 2746 (1995) and Phys. Rev. **D53**, 6241 (1996).

[4] R. Barbieri and G. Giudice, Nucl. Phys. **B306**, 63 (1988); G. Anderson and D. Castaño, Phys.Rev. **D52**, 1693 (1995).

[5] It has been argued that linear e^+e^- colliders operating at a $\sqrt{s} \sim 1000$ GeV have a reach comparable to the LHC. This is under the usual assumption that uncoloured sparticles are significantly lighter than their coloured cousins. The situation would be very different if the coloured sparticles are the light ones.

[6] Spontaneous R-parity violation via VEVs of doublet sneutrinos is phenomenologically excluded by measurements of Γ_Z at LEP, and so is possible only if additional singlet neutrino superfields are introduced. See *e.g.* C. S. Aulakh and R. N. Mohapatra, Phys. Lett. **B119**, 316 (1982); A. Santamaria and J. Valle, Phys. Lett. **B195**, 423 (1987) and Phys. Rev. Lett. **60**, 397 (1988).

[7] C. S. Aulakh and R. N. Mohapatra, Ref. [6]; F. Zwirner, Phys. Lett. **B132**, 103 (1983); L. J. Hall and M. Suzuki, Nucl. Phys. **B231**, 419 (1984); S. Dawson, Nucl. Phys. **B261**, 297 (1985); R. Barbieri and Masiero, Nucl. Phys. **B267**, 679 (1986); S. Dimopoulos and L. Hall, Phys. Lett. **B207**, 210 (1987); L. Hall, Mod. Phys. Lett. **A5**, 467 (1990).

[8] V. Barger, G. Giudice and T. Han, Phys. Rev. **D40**, 2987 (1989); G. Bhattacharyya, J. Ellis and K. Sridhar, Mod. Phys. Lett. **A10**, (1995); G. Bhattacharyya, D. Choudhury and K. Sridhar, Phys. Lett. **B355**, 193 (1995); G. Bhattacharyya and D. Choudhury, Mod. Phys. Lett. **A10**, 1699 (1995).

[9] H. Baer, C. Kao and X. Tata, Phys. Rev. **D51**, 2180 (1995).

[10] The impact of R-parity violation via baryon number non-conserving operators on the isolated like sign dilepton signal at hadron supercolliders has been discussed by J. Gunion and P. Binetruy, Davis preprint, UCD-88-32 (1988) and by H. Dreiner, M. Guchait and D. P. Roy, Phys. Rev. **D49**, 3270 (1994).

[11] Of course, if this lifetime is sufficiently long, it may be possible to see the displaced vertex from LSP decay and make the signal detection easier.

[12] F. Paige and S. Protopopescu, in *Supercollider Physics*, p. 41, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in *Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders*, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory, 1993), hep-ph/9305342.

[13] J. Botts *et. al.* Phys. Lett. **B304**, 159 (1993).

[14] D. Buskulic *et. al.* (ALEPH Collaboration), Phys. Lett. **B373**, 246 (1996); G. Alexander *et. al.* (OPAL Collaboration), Phys. Lett. **B377**, 181 (1996); P. Abreu *et. al.* (DELPHI Collaboration), CERN-PPE-96-075 (1996); M. Acciarri *et. al.* (L3 Collaboration) CERN-PPE-96-029 (1996).

[15] H. Baer, M. Drees, C. Kao, M. Nojiri and X. Tata, Phys. Rev. **D50**, 2148 (1994).

[16] See, however, H. Baer *et. al.*, Section VIII B in *Research Directions for the Decade*, Proceedings of the 1990 Snowmass Workshop, Snowmass, CO, E. Berger, Editor (World scientific, 1991).

FIGURES

FIG. 1. LHC reach contours in the m_0 *vs.* $m_{1/2}$ plane for various multi-jet plus multi-lepton plus $\not{E}_T$ signals in the minimal SUGRA model, but with hadronic $\widetilde{Z}_1$ decays. We show plots for *a)* $\tan\beta = 2$, $\mu < 0$, *b)* $\tan\beta = 2$, $\mu > 0$, *c)* $\tan\beta = 10$, $\mu < 0$ and *d)* $\tan\beta = 10$, $\mu > 0$. For all frames, we take $A_0 = 0$ and $m_t = 170$ GeV. The 1ℓ signal is denoted by solid contours, OS dileptons by large dashes, SS dileptons by small dashes, and the 3ℓ signal by dot-dashed contours. As discussed in the text, our simulation does not allow us to reach a definitive conclusion regarding the observability of the signal for the values of $m_{1/2}$ close to 100 GeV.

FIG. 2. Regions of the m_0 *vs.* $m_{1/2}$ plane where the multijet+$\not{E}_T$ signal should be observable when R-parity conservation is violated and $\widetilde{Z}_1$ decays hadronically. The frames are the same as in Fig. 1. The various squares represent points where the signal is observable according to the criteria stated in the text, and x's represent points where the signal is invisible. The statistical significance of each point is indicated: black squares are where at least 9 events pass all the simulation cuts, gray squares have 4-8 events passing, and open squares have just 1-3 events passing, and so have the largest statistical uncertainty.